AD-A140 640 DISPLAY-CONTROL COMPATIBILITY IN 3-D DISPLAYS(U) BOLT BERANEK AND NEWMAN INC CAMBRIDGE MA A W HUGGINS ET AL. 29 FEB 84 BBN-5584 N00014-80-C-0750 1/1

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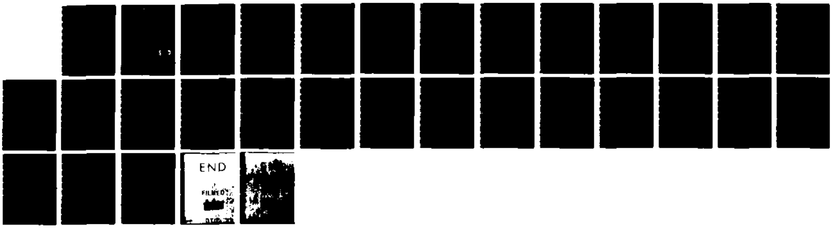

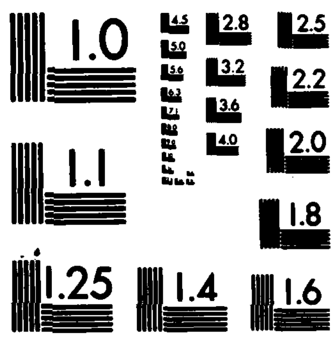

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Report No. 5584

Display-Control Compatibility in 3-D Displays

A.W.F. Huggins and David J. Getty

Final Report

February 1984

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER BBN Report No. 5584	2. GOVT ACCESSION NO. AD-A140640	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Display-Control Compatibility in 3-D Displays		5. TYPE OF REPORT & PERIOD COVERED 1 Jul 80-31 Dec 83 Final Report
		6. PERFORMING ORG. REPORT NUMBER BBN Report No. 5584
7. AUTHOR(s) A. W. F. Huggins and David J. Getty		8. CONTRACT OR GRANT NUMBER(s) N00014-80-C-0750
9. PERFORMING ORGANIZATION NAME AND ADDRESS Bolt Beranek and Newman Inc. 50 Moulton Street Cambridge, Mass 02238		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N 42; RR04209 RR0420901; NR 196-166
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Code 442 Arlington, VA 22217		12. REPORT DATE February 29, 1984
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Same		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N.A.

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; Distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N.A.

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

3-D Display, SpaceGraph, Display-Control Compatibility, Orientation, Cue Symmetry, Tracking, Depth Perception, Reaction Time, Trajectory Perception, Direction Perception, Multi-axis

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This research program explored human perceptual performance as influenced by display-control compatibility with a volumetric 3-D display technique. The work was organized into three phases. In the first, we studied how the speed and accuracy of the operator's decisions about the orientation of a displayed → next page

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20. Abstract (continued)

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BBN Report No. 5584

DISPLAY-CONTROL COMPATIBILITY
IN THREE-DIMENSIONAL DISPLAYS

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Introduction

Three-dimensional displays have reached the stage of development at which they can be seriously considered for a variety of applications. However, since the technology is new, not very much is known about the human-factors aspects of such displays: how accurately the operator can perceive various properties of objects presented in the display, and how the presence of the third dimension enriches both perception and performance of tasks monitored with the aid of the display. Bolt Beranek and Newman (BBN) had previously developed a prototype vibrating mirror 3-D display, called SpaceGraph. The operator views a CRT screen reflected in the mirror, and when the mirror is vibrated, the virtual image of the CRT face sweeps through a volume behind the mirror. True 3-D images can be drawn as arrays of points, with the X and Y coordinates of each point being specified by where on the CRT face a point is instantaneously displayed, and the Z, or depth coordinate is specified by the instant in the mirror cycle at which the point is displayed. As a result, the virtual image viewed by the observer is truly three dimensional, and therefore undergoes perspective transformations when the observer moves his head, exactly as if it were a real object. The mission of the work performed under this contract was to explore some perceptual and display-control compatibility issues in the context of the SpaceGraph display.

The work was organized into three phases. In the first, we studied how the speed and accuracy of the operator's decisions about the orientation of a displayed object (a cube) was affected as this orientation was varied relative to that of a fixed control (a cubical response box). In the second, we studied how accurately the observer can perceive and project a trajectory presented within the display, as a function of the trajectory's orientation. In the third phase, we used a real-time control task to measure directly the relative utility of the three dimensions of the display.

<u>PHASE 1: (a) Effects of Orientation</u> (Report No. 4724)

In the first phase, we studied the effects of differences of orientation on a spatial identification task. The observer was presented on each trial with an outline cube in the three-dimensional display. The bottom face of the stimulus cube was marked with an orientation cue that the operator used to identify the cube's orientation. One of the other five faces was also marked, with a "stimulus key" consisting of two concentric circles, and the observer's task was to identify which of the five faces was so marked (top, far, near, left, or right), and press the corresponding response key on a physical response cube.

A first, general finding was that the depth dimension of the display was less salient, or at least took longer to extract, even in a true 3-D display, than the lateral or vertical

dimensions. The difference in decision times was larger for pairs of stimuli that differed mainly in depth than for pairs that differed mainly in lateral or vertical position. However, responses to stimuli at the back of the display volume were made just as rapidly as stimuli at the front.

We found three different types of functions relating decision time to orientation of the stimulus cube: (a) flat functions in which the decision time was short and independent of stimulus cube orientation, and (b) two types of curvilinear function in which decision time increased and decreased systematically with orientation. The curvilinear functions appeared to be made up of two distinct parts: one involving a "plateau" shaped function with skirts; and the other consisting of a "peak" shaped function, with the peak involving long reaction times, and associated with orientations in which one or more of the axes in the display was reversed relative to the corresponding axis of the control.

Each of the three types of functions (flat, plateau-shaped, and peak-shaped) we associated with the observer's use of a particular strategy for selecting a response. The flat functions arose when the observer was able to determine the response uniquely from the spatial position of the stimulus button with respect to the world coordinates of the display volume. Thus, when the stimulus cube was rotated about its vertical Y-axis, the

top stimulus button was invariantly located at the top of the displayed cube for all orientations of the stimulus cube, because the rotation axis passed through the stimulus button. As a result, the observed decision times for the top response were unaffected by stimulus cube orientation for this task. The functions for the four other responses were strikingly different. Those for the front and back responses were plateau shaped, whereas those for the left and right responses were predominantly peak-shaped.

The next three experiments produced related results. These experiments involved rotations of the stimulus cube about (a) the depth or Z-axis, (b) the lateral X-axis, and (c) either the X- or the Y- or the Z-axis. When rotation was about only the lateral, X-axis of the cube, the spatial strategy was applied to the left and right stimulus buttons, consonant with their invariant position within the display. When rotations about any one of the three axes might be presented on any trial, no use of the spatial strategy was possible, since none of the stimulus keys remained in a constant position. Peak-shaped functions were associated with the left and right responses in three of the four experiments; the exception involved rotation about the lateral, X-axis, in which case the superior spatial strategy could be applied.

We hypothesized that the difference in performance between the left and right responses, on the one hand, and the near and far responses, on the other, was related to the symmetry of the cue we had used for indicating the orientation of the stimulus cube: a capital letter V drawn on the cube's bottom face, with its apex touching the front edge. The responses that were asymmetric with respect to this cue (near and far faces) yielded plateau-shaped functions, whereas those that were symmetric (left and right faces) yielded peak-shaped functions. Thus for the former pair, a relational strategy could be used, in which the spatial relationship between the stimulus key and the asymmetric aspect of the orientation cue indicated the correct response (e.g. the apex of the V "pointed" toward the near face). For the remaining pair of responses, the observer was forced to adopt a much less efficient strategy for selecting the response, a rotational strategy. This involved the observer mentally rotating into an orientation from which the cube appeared "head on" (i.e. the apex of the V pointed toward the observer), and then making a decision according to whether the stimulus button appeared on the left or right.

Thus the difference between the substantial display control incompatibility found for the left and right responses and the much smaller incompatibility found for the near and far responses appeared to be due to the cue chosen for indicating the

orientation of the stimulus cube. If so, it should be possible to reduce the incompatibility by using a more appropriate orientation cue.

<u>(b) Effects of Cue Symmetry</u> (Report No. 5101)

Our next three experiments tested the conclusions from the foregoing analysis. In the first, we again used a cue that was symmetric with respect to one dimension and asymmetric with respect to the other (a capital letter A), but we positioned the cue so as to interchange the responses associated with the symmetric and asymmetric aspects of the cue. That is, the left and right responses were associated with the asymmetric dimension of the cue, and the near and far responses were associated with the symmetric dimension. The results supported our analysis, in that the near and far responses now showed major display-control incompatibility effects. Their reaction time functions were sharply peaked, and the left and right responses showed much flatter plateau-shaped functions appropriate to use of the relational strategy.

The second and third experiments used an orientation cue that was asymmetric in <u>both</u> dimensions: a capital letter V on the bottom face of the cube, as before, but made asymmetric by the addition of a serif to the left upright of the V pointing toward the left face of the cube. The addition of this serif

significantly reduced the display-control incompatibility of both pairs of responses. The peak-shaped functions disappeared because observers were now able to use a relational strategy for all responses; and the responses associated with this strategy also became shorter as a result of all responses being selectable from only two instead of three strategies.

In a final experiment in the series, we examined the effects of prolonged practice on performance, by repeating the initial experiment exactly. The relative shapes of the functions had changed very little, although responses were significantly faster throughout, and the size of the peaks associated with the left and right responses was greatly reduced, due mainly to greatly reduced scatter in the response times resulting from elimination of the extremely long response times found in the first experiment.

<u>PHASE 2: Perception of Direction</u> (Report No. 5582)

A prime application area for 3-D displays could be in air traffic control. The possibility of integrating the plan-position and the vertical-situation indicator displays into a single display might be one of the more obvious goals. Before using such a combined display, it will be necessary to find out how accurately the operator can estimate and project directions within the display. Such projection would be needed for deciding whether a collision was likely to occur.

In the task that we developed, the observer was presented on each trial with an outline cube, of side about 18 cm, with a vector of 3 cm pointing from the cube's center toward one of the five sides of the cube away from the observer. The observer's task was to place a point, using a graphical tablet as an input device, on the cube's surface where the vector would pierce it if extended (the "piercing" point). The cube was composed of dotted lines along each of its twelve edges, and its center was marked by a small cluster of points. The vector originated in this cluster. The tablet was marked with an outline representing the five faces of the cube unfolded onto a flat surface, with the back face of the cube in the middle. As the observer moved the stylus within the outline, the point representing the piercing point moved correspondingly on the surface of the cube in the display.

There were 80 vectors, 16 pointed toward each of the five faces, generated by applying the rules of symmetry to only two different vectors. Each observer made 20 responses for each of the 80 vectors. Analyses of the data, performed separately for each observer, showed three principal effects that produced error in the piercing points. These effects appeared to be independent of one another, and to be superimposed in the data.

The first effect was a strong bias for the distribution of piercing points to fall along the linear extension of the vector

as projected from the observer's viewpoint upon the inner surface of the cube. The variance of the response distributions was always large in the direction of the projection, relative to that in the orthogonal direction. For vectors pointing at the top, bottom, or sides of the cube, the projections onto those faces were a set of lines parallel to the depth axis, so that variability in depth was much greater than variability in the frontal plane.

The second effect was a systematic error in piercing point away from the true target point toward the closest principal axis of the space (the vertical, lateral, and depth axes). Furthermore, the amount of angular error grew in proportion to the angular deviation of the target point from the closest principal axis. In effect, our observers tended to perceive oblique vectors as more nearly horizontal or vertical than they really were.

The third effect was a distortion of the perception of depth as a function of meridian in the frontal plane. In effect, the frontal plane was perceived as slanted in depth, with the top of the plane tilted back relative to the bottom. The amount and direction of the slant differed significantly across observers. We believe that this particular distortion may arise from a combination of two effects: (1) the known backwards slant of the vertical horopter, and (2) rotation of the frontal plane about a

vertical axis due to mild, uncorrected astigmatism in one or both eyes of our observers. We informally measured the axis and degree of astigmatism in each eye of our observers. The observed perceptual distortions are in general agreement for each observer with predictions based on the measured astigmatism.

PHASE 3: Perception and Control of Motion (Report No. 5583)

Several of the possible applications for a 3-D display such as SpaceGraph could involve the real-time control of images presented on the display. Our earlier experiments, and other informal observations made under a variety of conditions, suggested that the depth dimension of the displayed images or their position was perceived less quickly and less accurately than the lateral or vertical dimensions. The third phase of work was performed to quantify these differences, and to determine their causes.

The task selected was a closed-loop tracking task with a first-order unstable controlled element, and with a sum-of-sines disturbance function added to the loop input to perturb the system away from its rest state. This task was implemented for one-, two-, and three-axis tracking, although only the one- and two-axis tasks were used in the current work. Performance was compared on five separate tracking-tasks. Three of these were single-axis tasks, one for each of the major axes of the display

(lateral or X, vertical or Y, and depth or Z). The remaining two tasks were two-axis tasks, in which the controlled element moved in a plane containing the lateral and the vertical axes (XY), or the lateral and the depth axes (XZ). In all tasks, the controlled element was a single point. The display volume was outlined by a cube about 18 cm on the side, and an irregular array of dimmer points appeared behind the back face of the cube to provide a textured background as a reference for the moving point. The center of the cube, corresponding to the rest state of the controlled element, was marked by two points offset slightly from the center along the main diagonal. The control was a two-axis force stick ("stiff" stick). During preliminary studies, the difficulty of the task was specified by varying the frequency (time constant) of the pole of the instability, so that it was just possible to maintain control in the most difficult of the five tasks. After some preliminary familiarization, the observers were trained concurrently on all five tasks during daily one-hour sessions. Experimental data were collected on the eighth and ninth sessions. The data in the ninth session were collected to test the need for the textured background. The background array was removed for this session, so the stable referents in the display, along with the controlled point, were the outline cube and the two points marking its center.

Performance on the lateral X and vertical Y axes were very similar, as expected. Secondly, performance on each axis in the two-axis XY task and on the X axis in the XZ task was very similar to those on the component single-axis tasks; and in agreement with earlier findings that two independent tracking tasks can be performed concurrently without loss, if the display and control are appropriately integrated. The most interesting comparisons were made between the single-axis X and Y tasks, on the one hand, and the single-axis Z-task, on the other. Performance was significantly worse on the depth axis, with the tracking score (standard deviation of the position of the controlled point) about 60% larger than that found for either the lateral or vertical axes.

Inspection of plots of the operator's gain, phase, and remnant as a function of frequency suggested that there was little difference between the phase functions for the depth and frontal axes, but that observers reduced their gain substantially when tracking in the depth dimension, and remnant power was appreciably higher at low frequencies. The experimental data were modeled by iteratively modifying the parameters of the optimal control model of the human operator, separately for each axis. Comparison of the parameters for the lateral and vertical (i.e. frontal) axes, on the one hand, and the depth axis, on the other, showed that observation noise levels were about 4 dB

higher for the depth axis, and in addition the operator delay was increased substantially (by about 100-150 ms). This result was confirmed informally by repeating the model runs with the delay parameters fixed, and finding that this produced a substantially worse fit to the data. A possible conclusion is that more processing was required to extract the position of the target when tracking in the depth dimension than when tracking laterally or vertically, and in addition it was harder to determine the position of the controlled object in the depth axis tasks. An alternative explanation that cannot be ruled out is that the operator was not operating linearly in the depth dimension, but rather made no response until some threshold was exceeded. Since linear operation is required by the optimal control model, this would cast doubt on the model results.

IMPLICATIONS FOR FURTHER RESEARCH

(a) Orientation

In our present research, we found that the time required to perceive the orientation of a displayed object is shorter when an observer is able to use a relational rather than a rotational strategy. This requires that the object be asymmetric along each of its principal axes. These results were obtained using static views of an object at particular orientations. Further work is needed to determine how rapidly and accurately an observer can

perceive and follow the changing orientation of a dynamically tumbling and translating object. Such results would be important in applications involving dynamic displays, such as docking with a tumbling platform or tracking a feature on a tumbling object.

(b) Direction

Many practical applications of 3-D displays will require that observers be able to accurately perceive direction within the space. We observed two major types of systematic error when observers predicted the point at which a vector would pierce the surface of an enclosing cube. Further research is needed to determine the bases of these perceptual distortions, and the means for minimizing or eliminating their effects in applications.

One observed distortion was the displacement of perceived piercing points away from the true target point towards the closest principal axis (vertical, lateral, or depth) of the space. One interpretation suggests that we tend to perceive a vector as more nearly vertical or horizontal than it is truly. However, because of the presence of visible edges in the displayed cube, it is also possible that the observed displacement represents a sensory or perceptual repulsion of the perceived piercing points away from the visible edges. Further research is needed to separate these two confounded explanations.

This might, for example, include an experiment in which the visible cube edges are removed so that the observer-controlled point moves about on an invisible surface.

The second observed distortion was, in effect, an oblique slant of the frontal plane, different for each observer. We have suggested that this distortion is due to a combination of several perceptual effects, one arising from mild uncorrected astigmatism in one or both eyes of our observers. Further experimental work is needed to test this explanation, possibly including experiments in which perceptual effects are measured after inducing controlled amounts of astigmatism along known meridians.

(c) Motion

The experiments on tracking in a 3-D display only scratch the surface of possible research in this area. More work is needed to determine whether the increased processing delay found when tracking in the depth dimension is real, and if so, whether it is possible to modify the display so as to reduce its effects. The controlled object consisted of only a single point, with the result that stereo-optical disparity was the only cue to its depth. If a larger object were controlled, its changes in subtended retinal angle would offer additional cues. A second area where more research is needed is on extending the tracking task to three dimensions, where the controlled object is

controlled in all three dimensions simultaneously, and to six dimensions, where the attitude of the controlled object is under control as well as its position. These tasks are of interest because they approach real-world applications, and also because they can be used to answer questions about the appropriateness of various types of controls.

A further area where research is needed is the control of 3-D objects when the coordinate axes of the control mechanism does not correspond to those of the displayed object.

(d) Control Mechanisms

In the first set of experiments, the communication between the operator and the display was in one direction only; the display showed an image, and the operator viewed that image and selected a response. The response had no effect on the display other than to begin a new trial. The "control" device with which the response was made had the same shape as the displayed object (a cube) because in these experiments we were more interested in the effects of mismatches of orientation between the displayed image and the control than in the effects of less optimal mappings from the display onto the control device. There is little reason to doubt that the findings from the standard human-factors literature apply, i.e., responding becomes progressively more difficult, slower, and less abstract, as the

relationship between display and control device moves from strict isomorphism, to a less-spatial mapping, and then to a more-abstract mapping. The significant performance improvement obtained in the experiments on orientation when the control and displayed image were in corresponding orientations suggested that, where the gravitational vertical in the displayed image always corresponded to the vertical axis of the display device, it would be useful to give the operator a control device consisting of a horizontal wheel with which to rotate the orientation of the displayed image to an optimal position. Further research is needed to test this suggestion.

A similar control device could be useful in a refinement of the set of experiments on the perception of direction. Here, the highest accuracy in projecting the vector within the display volume occurred when the observer's viewpoint was most nearly aligned with the vector (i.e. it was nearly possible to sight down it). To allow the operator to sight down any vector, the control device needs two control axes. A track-ball might be a good way to accomplish this; and the top of the ball could be rolled in the direction that the vertical axis should be tipped. Another option would be to use a joy-stick connected so that a departure from its (spring-loaded) vertical orientation would cause the vertical axis of the display volume to incline such that it remained parallel with the joystick.

In the second and third sets of experiments, the loop from control device to display was closed, so that movements of the control device affected the contents of the display. Operators had no difficulty in understanding the mapping of the control device onto the resulting effects that appeared on the display. Use of the tablet, which is a two-dimensional input device, was appropriate in the experiment on trajectory projection, because we wished the controlled point to move only on a surface. The fact that operators were able to use the forward-backward direction of movement of the force stick to control either the vertical or the depthwise movement of the controlled element in the tracking task suggested that a three-dimensional force stick would be an appropriate input device for a three-dimensional control task.

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